| (51) International Patent Classification 6 : | | (11) International Publication Number: | **WO 99/59182** |
|---|---|---|---|
| **H01J 37/02, 37/317, 49/02** | **A1** | (43) International Publication Date: | 18 November 1999 (18.11.99) |

(54) Title: ION BEAM APPARATUS AND A METHOD FOR NEUTRALISING SPACE CHARGE IN AN ION BEAM

(57) Abstract

A source of thermionic electrons is provided inside the flight tube of a magnet, especially an analysing magnet, and extends along the beam flight path. This allows space charge to be neutralised along the beam's axis in spite of severely restricted electron mobility in this direction owing to the presence of substantially transverse magnetic field. Thermionically emitted electrons may contribute directly to the neutralisation of space charge in positive ion beams, or, in the case of negative ion beams, indirectly by ionizing residual or deliberately introduced neutral gas atoms or molecules. Examples are described and claimed in which the source is arranged outside the nominal beam envelope in the flight tube, but linked to the beam by magnetic flux generated in the flight tube. This reduces erosion of the source by the beam and so reduces beam contamination. In these examples, an important feature is the provision of electron repellers to reflect electrons back and forth across the beam. Alternative arrangements are described and claimed in which the source is positioned inside the beam. The thermionic electron source may comprise an array of filaments, and preferably is negatively biased with respect to the flight tube. Adjustment of this bias enables the energy of emitted electrons to be controlled.

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ION BEAM APPARATUS AND A METHOD FOR NEUTRALISING SPACE
CHARGE IN AN ION BEAM

The present invention is concerned with
5    neutralising space charge in ion beams travelling
through regions of applied magnetic field, and in
particular, although not exclusively, with
neutralising space charge in an ion beam as it travels
through the flight tube of an analysing magnet.
10    An analysing magnet generates a substantially
uniform magnetic field in its flight tube, causing an
ion travelling through the flight tube to follow a
curved path in a plane perpendicular to the direction
of the magnetic field.  The radius of the curved path
15    is given by:

$$r=mv/qB=(2Em)^{\frac{1}{2}}/qB$$

where v,E,m and q respectively are the velocity,
kinetic energy, mass and charge of the ion, and B is
20    the magnitude of the magnetic flux density in the
flight tube. The analysing magnet can therefore be
used to resolve spatially (in a dispersion plane
perpendicular to the magnetic field in the flight
tube),ions in a beam according to their energy, mass
25    and charge.
In ion implanters, an analysing magnet is used in
conjunction with a selection slit to select ions of
the required species from an incident beam for
implantation in a target semiconductor substrate.
30    Typically, the incident beam will comprise ions having
substantially the same energy, and the magnet is
arranged to focus those ions having the desired
mass/charge ratio at the selection slit so that only
they pass through the slit and go on to impinge on the
35    target.

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In spectrometry applications, analysing magnets are used to resolve ions in a beam according to their mass, energy and charge for separate detection.

5          Ideally, for both ion implantation and spectrometry applications, ions in the beam entering the flight tube having the same energy, charge and mass should all be focused by the analysing magnet onto a common line, perpendicular to the dispersion
10      plane, as they exit.

However, in the absence of any neutralising effect, a beam containing only ions of a particular polarity will experience space charge effects. The mutual repulsion of the ions in the beam tends to
15      cause the beam to diverge or "blow up". This mutual repulsion means that the position at which an ion exits the magnet is no longer solely determined by its incident velocity, mass and charge, and the applied magnetic field.

20          In ion implantation applications, although an incident ion may have the desired mass/charge ratio, because of space charge effects it may not be focused on the selection slit and so may not reach the target. This reduces the ion implantation current reaching the
25      target from a given source and increases the process time required to achieve a desired implantation dose. In addition, space charge effects may result in an increased number of incident beam ions hitting the sides of the flight tube. This further reduces the
30      implantation current reaching the target and can result in contamination of the target by particles sputtered off the flight tube.

Similarly, in spectrometry applications, beam "blow up" inhibits the spatial resolution of different
35      ions and reduces signal intensity.

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In applications where a scanning magnet is used to deflect an ion beam (for example to scan the beam across a target) beam blow up inside the magnet is also undesirable. It reduces beam intensity and
5    control accuracy.

The effect of beam space charge is especially severe for relatively low energy beams (e.g. 1-2 keV) since for the same beam current there is a higher density of ions in a low energy beam.
10    In regions of zero electric field, such as the flight tube of an analysing or scanning magnet, self neutralisation of ion beams tends to occur through the production of electrons and positive ions resulting from collisions between beam ions and atoms of
15    residual gas in the vacuum chamber through which the beam is passing. However, this self neutralisation may be insufficient adequately to reduce beam blow up. This is particularly true for relatively low energy ion beams, as, at low energies, the cross sections for
20    electron production during interaction between the beam ions and residual gas atoms are extremely small.

Also, some self neutralisation may occur as a result of local electron production from the beam striking the inside of the flight tube along the
25    entire beam path through the magnet. Again however, this may be insufficient to reduce beam blow up to acceptably low levels, and in any case is to be avoided as it results in beam loss and unwanted particle generation.
30    In regions of zero electric field and zero magnetic field (i.e. "drift space") a known technique to neutralise space charge is to flood the region through which the ion beam travels with low energy (typically a few eV) electrons or ions, produced, for
35    example, in a plasma chamber adjacent to the beam

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flight path.  In this drift space the electrons or
ions are mobile and can move along and across the beam
to minimise beam potential.

In regions of applied magnetic field however, the
magnetic field severely limits the mobility of these
electrons or ions.  In applied fields of sufficient
magnitude to deflect beams of ions with energies in
excess of, say, a few keV, low energy charged
particles, and electrons in particular (with their
small mass,) will follow paths having circular
projections of very small radii on a plane
perpendicular to the direction of applied field. In
effect, the electrons are restricted just to following
the magnetic field lines. They have substantially zero
mobility perpendicular to the applied field, which in
the case of analysing magnets or scanning magnets
means that the electrons have substantially zero
mobility along the beam axis.

In regions where the electric field is nominally
zero, such as inside the earthed flight tube of an
analysing magnet, there may in fact be a small amount
of electron motion perpendicular to the direction of
applied magnetic field owing to the presence of
various small electric fields such as those resulting
from the beam itself.  This motion is known as E x B
motion.  However, in such nominally E-field-free
regions, electron mobility along the beam is, in
general, very restricted.

Thus it is not possible to neutralise beam space
charge inside regions of applied field by introducing
low energy charged particles to adjacent drift space
regions as the charged particles will not be able to
migrate into the beam.

According to a first aspect of the present
invention there is provided ion beam apparatus

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comprising:

a analysing magnet including a flight tube for receiving and conveying through the magnet a beam of ions, the magnet being operable to generate a
5  substantially uniform magnetic field in the flight tube to deflect beam ions according to their mass/charge ratio in a dispersion plane perpendicular to the direction of said uniform magnetic field; and

a thermionic electron source inside the flight
10  tube, arranged adjacent and outside a nominal cross section of a beam of ions travelling through the magnet and extending along a nominal flight path of a beam travelling through the magnet,

the thermionic electron source being further
15  arranged such that the projection of the thermionic electron source on the dispersion plane and the nominal projection on the dispersion plane of an ion beam travelling through the magnet overlap at a plurality of positions along the nominal flight path
20  of the beam.

Thus, magnetic flux generated by the magnet may link the thermionic electron source and a beam of ions travelling through the magnet at a plurality of positions along the flight path, and electrons may be
25  emitted thermionically from the source into the beam at these positions.

This enables space charge to be neutralised at a plurality of positions along the beam in spite of low electron mobility along the beam, and so reduces "blow
30  up", keeping the beam tight. The thermionic electron source is positioned outside the nominal beam envelope to reduce beam contamination resulting from sputtering off the source and the associated erosion of the source.

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In the presence of the magnetic field generated by the analysing magnet, electrons emitted from the thermionic electron source will simply follow field lines passing through the source. These field lines

5    will be perpendicular to the dispersion plane of the magnet. Only those emitted electrons travelling along field lines which also link the ion beam will, therefore, enter the beam and contribute to neutralisation of its space charge (either directly,

10   in the case of a beam of positive ions, or, in the case of a beam of negative ions, by colliding with residual or deliberately introduced gas atoms or molecules to produce positive ions).

Clearly, the greater the degree of overlap

15   between the projections on the dispersion plane of the thermionic electron source and the ion beam, the greater the proportion of electrons emitted from the source that are able to enter the beam.

Advantageously, the thermionic electron source

20   may extend substantially in a plane spaced from and parallel to the dispersion plane. In an analysing magnet with a nominally horizontal dispersion plane, the thermionic electron source may therefore be arranged in a plane just above, or just below the

25   nominal beam cross section.

In a preferred embodiment the thermionic electron source is positioned as close as possible to the nominal beam cross section to maximise the proportion of the flight tube cross section available for beam

30   transport.

In certain embodiments, the thermionic electron source comprises a longitudinal electrically conductive filament running along the nominal flight path, above and substantially parallel to the nominal

35   centre of an ion beam travelling through the analysing

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magnet.   The filament may therefore be linked to the
beam by magnetic flux along a substantial part of its
length, and so can be used to emit electrons
thermionically to neutralise space charge along a
5      large fraction of the beam's path length through the
magnet.
        A plurality of spaced-apart longitudinal
filaments may be used to neutralise space charge both
along the length and across the width of a beam.
10         In a further preferred embodiment, the thermionic
electron source comprises a plurality of transverse
filaments, spaced along the flight path, and each
extending across the nominal beam width.
        The transverse filaments may for example, be
15     connected to bus bars at opposite sides of the beam,
or may be in the form of hairpins, connected to two
separate bus bars at the same side of the beam.
Hairpin geometry provides the advantage that the
filaments are less prone to breaking as a result of
20     relative movement of the bus bars, or thermal
expansion or contraction.
        The transverse filaments provide the advantage of
enabling space charge to be neutralised across the
beam at a plurality of locations along its path
25     through the magnet.
        The thermionic electron source may comprise an
array or grid of filaments, which may be planar and,
for example, be machined or cut from a graphite sheet.
        Heat shields may be incorporated between the
30     thermionic electron source and the inside of the
flight tube to reduce the power needed to maintain the
source at a temperature sufficient to yield a desired
emission current.
        A wide variety of materials may be used for the
35     filament or filaments, including, for example,

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tungsten.

In a preferred embodiment however, graphite
filaments are employed. For ion implantation
applications in particular, graphite filaments are
5       desirable because carbon sputtered off the filaments
as a result of beam strike is a more tolerable beam
contaminant than are metal atoms or ions.

In cases where the beam travelling through the
magnet comprises just positive ions, the
10      thermionically emitted electrons may neutralise the
beam space charge directly. The electrons travel
along flux lines into the beam, and once inside
contribute to space charge neutralisation.

In the case of beams comprising negative ions
15      travelling through the magnets, thermionic electrons
may be used to ionise residual gas atoms or molecules
in the partial vacuum of the flight tube. The
positive ions produced by collisions between the
thermionic electrons and the residual atoms or
20      molecules may then contribute to the neutralisation of
beam space charge.

To facilitate the neutralisation of negative ion
beams, charge-neutral atoms or molecules may
deliberately be introduced into the flight tube for
25      ionisation by thermionically emitted electrons.

A thermionically emitted electron entering the
beam will, in general, only remain in the beam if it
suffers a collision inside the beam, and as a result
loses energy. Otherwise, it will have sufficient
30      energy to escape any beam potential well and will
cease to contribute to beam space charge
neutralisation.
Collisions with ions or neutral atoms may be elastic
or inelastic. At very low energies, below the
35      thresholds for excitation and ionisation, elastic

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collisions, which involve very small energy transfers,
dominate and the electrons may simply bounce off their
collision partners and escape from the beam.
Collisions with other electrons would involve greater
energy transfer, but the collision cross-section is
very small. The inelastic collision cross-sections can
be increased significantly by increasing the electron
energy by applying a negative bias to the thermionic
electron source. In preferred embodiments therefore,
the thermionic electron source is negatively biased
with respect to the flight tube, and this bias voltage
may be adjusted to control the energy of the emitted
electrons.

This bias enables the injection of electrons into
the beam to be controlled and also provides the energy
required to ionise the background (i.e. residual) gas
which is important in the case of the space charge
neutralisation of negative ion beams.  Control of
electron emission energy is also important in the case
of positive ion beams in that slow positive ions
produced by collisions between residual, or
deliberately introduced, neutral gas atoms or
molecules and low energy emitted electrons are an
important feature of space charge neutralization
because they help to trap electrons.  If slow negative
ions are produced, an unlikely process in most gases,
they too would assist in the neutralization of the
positive ion space charge.

A beam of positive ions may be surrounded by a
sheath of negative space charge which provides a
potential barrier to the entry of thermionically
emitted electrons into the core of the beam.  Biasing
the source can provide the emitted electrons with
sufficient energy to penetrate this barrier.

Depending on the particular application, optimum

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biases in the range 3V to 70V have been found,
although optimum values outside this range may be
expected.

Advantageously, one or more electron repellers,
5    may be arranged inside the flight tube and outside the
nominal beam envelope to reflect electrons escaping
the beam back into the beam. The electron repellers
are negatively biased with respect to the thermionic
source, and the bias may be adjustable. In one
10   application, a weak optimum bias of 3V was found. The
reflectors may be positioned on opposite sides of the
beam, and enable the lifetime of electrons in the beam
volume to be extended. Energetic electrons which, in
the absence of collisions, would not remain in the
15   beam, may be reflected back and forth substantially
along field lines linking opposing repellers. The
"confinement" of electrons between opposing repellers
is possible because the mobility of electrons in
directions perpendicular to the applied magnetic field
20   is severely restricted.

The repellers may be planar, and may comprise
graphite sheets. The repellers may in fact also
function as heat shields.

According to a second aspect of the present
25   invention there is provided ion beam apparatus
comprising:

an analysing magnet including a flight tube for
receiving and conveying through the magnet a beam of
ions, the magnet being operable to generate a
30   substantially uniform magnetic field in the flight
tube to deflect beam ions according to their
mass/charge ratio in a dispersion plane perpendicular
to the direction of said uniform magnetic field; and

a thermionic electron source inside the flight
35   tube, extending along the nominal flight path of said

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beam and being arranged inside the nominal envelope of
said beam.

The term "envelope" is used to denote the three-
dimensional surface nominally bounding the beam, i.e.
5    it represents the nominal extent of the beam.  An
object placed inside the nominal beam envelope will,
therefore, nominally be struck by the beam. An object
inside the nominal beam envelope is in the nominal
path of the beam.

10    By positioning the source at least partially
inside the beam, low energy electrons may be emitted
which have insufficient energy to escape the beam
potential well.  These electrons may therefore remain
in the beam for a significant time and contribute to
15    space charge neutralisation.  Again, the emitted
electron energy may be controlled by varying the bias
on the source with respect to the flight tube.

The source inside the beam may comprise an array
of filaments, which may be planar or may follow a
20    curved surface including the nominal beam centre line.

The array may extend over at least part of the
height and/or the width of the beam to provide more
homogeneous space charge neutralisation.

The array may comprise straight, curved, hair-pin
25    or other geometry filaments, and may be a grid.

The source may be electrically conductive, may
comprise carbon, and/or may comprise refractory
material.  The source may be arranged to be heated
electrically, or by the beam, or both.

30    In order to reduce contamination of the beam
conveyed to the remainder of the apparatus, downstream
of the magnet, the parts of the thermionic electron
source inside the nominal beam envelope (i.e. these
parts nominally subjected to beam strike) may be
35    arranged to be out of line of sight with the selection

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slit at the exit of the flight tube.

According to a third aspect of the present invention there is provided ion beam apparatus comprising:

5      a magnet arranged to generate a magnetic field in a flight tube to deflect a beam of ions travelling through said flight tube; and

a thermionic electron source inside said flight tube, extending along the nominal flight path of said 10    beam and arranged to emit electrons thermionically into said beam.

The source may be arranged outside the nominal beam envelope and further arranged to be linked to the beam at a plurality of positions along its path by 15    magnetic flux generated by the magnet, or the source may be arranged at least partially inside the nominal beam envelope.  The source may comprise an array of filaments, and the apparatus may further comprise electron repellers, heat shields, and means for 20    biasing the source and the repellers.

According to a fourth aspect of the present invention there is provided a method of neutralising space charge in a beam of ions travelling in a flight tube through a magnet, the method comprising the steps 25    of:

providing a source of thermionic electrons inside the flight tube, adjacent and outside the nominal cross section of the beam and extending along the nominal flight path of the beam;

30      arranging the thermionic electron source to be linked to the beam at a plurality of positions along the nominal flight path by magnetic flux generated by the magnet; and

emitting electrons thermionically from the 35    thermionic electron source.

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According to a fifth aspect of the present
invention there is provided a method of neutralising
space charge in a beam of ions travelling in a flight
tube through a magnet, the method comprising the steps
5    of:
providing a source of thermionic electrons inside
the beam, said source extending along the beam; and
emitting electrons thermionically from said source.

10       The magnet may, for example, be an analysing
magnet, a scanning magnet, or a magnet arranged to
deflect the beam for other purposes. It will be
apparent that the term "flight tube" is used simply to
denote the region of space inside the magnet through
15   which ion beam travels. The "flight tube" in general
need have no sides as such, but typically comprises an
electrically conductive tube inside which the electric
field is arranged to be zero.
Embodiments of the present invention will now be
20   described with reference to the accompanying drawings
in which:
Fig 1 is a schematic plan view of a first
embodiment of the present invention:
Fig. 2 is a schematic perspective view of part of
25   the embodiment shown in Fig 1;
Fig. 3 is a schematic plan view of a further
embodiment;
Fig. 4 is a schematic plan view of an embodiment
of the present invention;
30       Fig. 5 is a schematic cross section of part of
the embodiment shown in Fig 4;
Fig. 6 is a schematic cross section of part of a
further embodiment;
Fig. 7 is a schematic diagram of part of the
35   embodiment of Fig. 6;

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Fig. 8 is a schematic perspective view of part of
a further embodiment; and

Fig. 9 is a schematic diagram of the cross
section of part of an embodiment of the present

5      invention.

A first embodiment will now be described with
reference to Fig 1 which shows a highly schematic plan
view of an analysing magnet 1 generating a
substantially uniform magnet flux density B throughout

10     its flight tube 2.  In this example the direction of
the magnetic flux B is into and perpendicular to the
plane of the paper and so the dispersion plane is
parallel to the plane of the paper.  A beam 3 of
positive ions, all having substantially the same

15     energy, enters the flight tube 2 and is deflected by
the magnetic field.  In this example the beam is
slightly divergent as it enters the flight tube, and
the analysing magnet is arranged to focus only those
ions in the beam that have the desired mass/charge

20     ratio on a selection slit 11 in a selection electrode
10 positioned downstream of the exit from the flight
tube.  The nominal profile of the path through the
magnet of the desired ions from the incident beam 3 is
shown bounded by broken lines 31.  As the figure is a

25     plan view, this nominal profile 31 is also the nominal
projection on the dispersion plane of the path of the
desired component of the incident beam.

Ions in the incident beam which have different
mass/charge ratios will follow curved paths of

30     different radii through the magnet and will strike the
walls of the flight tube 2 or the selection electrode
10.

A thermionic electron source in the form of a
single electrically conductive filament 5 is

35     positioned inside the flight tube, above the nominal

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beam path to reduce the number of ions striking the
filament and sputter etching it away.  In this example
the filament 5 extends along the entire length of the
beam path in the magnet and out into drift space.  In
5       other examples, the filament may be shorter, located
wholly within the flight tube.  Also, in other
embodiments the filament may comprise a plurality of
straight sections, rather than being a continuous
curve.
10          The filament 5 is located in the flight tube
above the beam by means not shown in the figure, and
runs substantially parallel to the nominal centre of
the beam. In fact, in this embodiment the projection
of the filament onto the dispersion plane is
15      coincident with the projection of the nominal beam
centre line.  A power supply 9 is connected to the
filament 5 to heat it to a temperature sufficient to
cause the filament to emit electrons thermionically.
The positioning of the filament 5 ensures that it is
20      linked to the nominal beam profile 31 along its entire
length inside the flight tube 2 by magnetic flux B.  A
perspective view of a section of the filament linked
by magnetic flux to the nominal beam profile is shown
schematic in Fig 2. Also shown in the figure is the
25      path of an electron thermionically emitted from the
filament.  The electron follows a helical path along
the magnetic flux passing through the filament,
although the figure greatly exaggerates the radius of
the circular component of this helical motion.  The
30      electron is only able to enter the beam because this
flux also links the beam; electron mobility
perpendicular to the applied field direction is almost
zero.  Once inside the beam, the electron is able to
provide some neutralisation of the beam space charge.
35          In an embodiment similar to that shown in fig 1,

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a tungsten filament was suspended above the nominal
median ray of a beam inside a flight tube and
electrically heated to temperatures of approximately
2000°C and higher to cause thermionic emission of
5     electrons into the beam. For a beam of 2keV boron
ions, as the filament temperature was increased to
increase thermionic electron emission current, an
increase in peak intensity and a decrease in the width
of the beam emerging from the analysing magnet was
10    observed, a result attributable to neutralisation of
space charge in the beam by thermionically emitted
electrons. It was also observed, however, that too
high an emission current could actually reduce the
beam current exiting the magnet, and so control of
15    filament temperature is desirable to optimise space
charge neutralisation.

For an incident ion beam of $^{10}$B and $^{11}$B isotopes,
thermionic emission from a tungsten filament was found
to enhance only the exiting beam corresponding to one
20    isotope. This effect is attributable to poor spacial
overlap between the projections of the filament and
the path of ions of the other isotope onto the
dispersion plane.

In order to improve space charge neutralisation
25    across the beam, a plurality of substantially
longitudinal filaments may be employed. Such an
embodiment is shown in Fig 3. In this example five
substantially parallel filaments are located so as to
be linked by the flight tube magnetic field to the
30    beam at a plurality of positions along its length and
across its width. Means for heating the filaments,
which may of course comprise any suitable material,
are provided (although not shown in the figure), as
are means for supporting the filaments in position in
35    the flight tube.

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An alternative way of providing space charge
neutralisation at a plurality of positions along the
beam and across its width is to employ a series of
substantially transverse filaments, as shown
5      schematically in Fig 4. In general, transverse
filaments, and electrical connection to the filaments
in particular, are easier to engineer than
longitudinal filaments. In this embodiment, the
filaments 5 are spaced from each other along the
10     length of the beam, and each transverse filament 5
extends across the nominal beam width, connecting to
bus bars 6 on either side of the beam flight path.
       The filaments are distributed along the beam and
form a substantially planar array. Although in the
15     figure the filaments 5 and bus bars 6 are shown as
separate components electrically connected, in
alternative embodiments the filaments and bus bars may
be formed from a single graphite sheet.
       Electrical currents are passed through the
20     filaments by means of the bus bars, to heat the
filaments and cause them to emit electrons
thermionically. The space charge neutralisation
apparatus inside the flight tube 2 is incorporated in
an assembly 50, whose cross section is shown
25     schematically in Fig 5. The outer casing of the
assembly 50 can in fact also be referred to as a
flight tube as it surrounds the ion beam as it travels
through the magnet 1. The casing 50 is electrically
conductive and earthed to screen the beam from
30     external electric fields. The filaments 5 are
negatively biased with respect to the casing 50 and
flight tube 2, and this negative bias is adjustable to
control the energy of the thermionically emitted
electrons.
35        Referring now to Fig. 5, the transverse filament

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5 is fixed and electrically connected to bus bars 6 by
means of fixing screws 52 and is linked to the nominal
cross section of the beam envelope 32 across its whole
width by the magnetic field in the flight tube. In
this example, the transverse filaments are positioned
above the nominal beam cross section and lie in a
plane spaced from and substantially parallel to the
dispersion plane. The neutralising assembly 50 further
comprises heat shields 51, 51a arranged between the
filaments 5 and the top and bottom walls of the flight
tube 50.  These heat shields reduce the power required
to heat the filaments to temperatures sufficient to
yield the required emission currents.

The heat shields in this example are
substantially planar graphite sheets extending along
the nominal beam flight path and fully across the
nominal beam width.

The inner heat shields 51a are negatively biased
with respect to the filaments 5 and act as electron
repellers, able to reflect electrons travelling away
from the beam, along magnetic flux lines, back towards
the beam.  Thus, although an electron emitted from the
filament may have sufficient energy to pass through
the beam, the repellers may reflect the electron back
towards the beam and so increase its contribution to
space charge neutralisation.

The bias voltage applied to the inner heat
shields 51a is variable, and may be adjusted to
achieve optimum neutralisation.  For one application,
a weak optimum was observed with a bias voltage of
-3V.

The filament 5 may be formed from any suitable
material, including for example tungsten or graphite.
In ion implantation applications in particular it may
be preferable to use graphite filaments, as carbon

contamination of the beam (and hence of the target
substrate) caused by parts of the beam striking the
filaments and sputtering off material is much more
tolerable than metal contamination.  In addition, any
5     carbon deposits inside the apparatus resulting from
sputtering off the filaments are more easily removed,
for example by oxidation and evacuation.

On the other hand, it may be desirable to use
tungsten or other metal filaments for their superior
10    robustness.

It will be apparent that in other embodiments, a
thermionic electron source comprising a combination of
transverse and longitudinal filaments may be employed,
for example in the form of a fine wire mesh positioned
15    "over" the beam path.

In general, the greater the spatial frequency of
the filaments along and across the beam, the greater
the homogeneity of space charge neutralisation.

Fig. 6 shows a schematic cross section of a
20    neutraliser assembly 50 in accordance with a further
embodiment of the present invention. The casing of the
assembly is optional, but in this example is made from
aluminium and is grounded.  The casing may be
integrated with the vacuum flight tube 2 or even the
25    analyser magnet poles themselves.

Inside the casing, a plurality of substantially
hairpin-like graphite filaments 5 are spaced along the
nominal beam flight path, each filament extending in a
plane parallel to the dispersion plane and across the
30    beam width (i.e. they are substantially transverse
filaments). Connecting means 52 connect each filament
5 to bus bars 6 positioned on the same side of the
beam. The filaments form a substantially planar array.

The direction of the flight tube magnetic field
35    is shown, and, in the arbitrary orientation of the

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figure, the filaments are accordingly positioned
adjacent and underneath the nominal beam cross section
32.

Outer graphite heat shields 51b are grounded, as
5    are the inner side heat shields. In contrast, the
inner top and bottom heat shields 51a are negatively
biased with respect to the filaments 5 to act as
electron repellers.

The use of electron repellers is an important
10   factor in achieving appreciable beam space charge
neutralisation in embodiments where the thermionic
electron source is arranged outside the nominal beam
envelope.

The support posts 59 are non-conductive and may,
15   for example, be alumina, or graphite with alumina
collars.

Fig. 7 shows a highly schematic plan view of the
arrangement of just the transverse hairpin filaments 5
and bus bars 6 of the embodiment of Fig 6. As can be
20   seen, the bus bars follow curved paths substantially
parallel to the beam (ie. following the arc of the
analysing magnet) and the hairpin filaments are
equispaced along the bus bars.  In this example, the
hairpin filaments are V-shaped, although of course
25   other geometries are possible.  The hairpin or V-
shaped geometries, where the filaments connect to bus
bars on the same side of the beam, are particularly
advantageous for graphite filaments, which are
brittle.  Brittle straight graphite filaments
30   connected to bus bars on either side of the beam have
a tendency to break as a result of relative movement
of the bus bars and/or thermal expansion effects.
Hairpin geometry alleviates this problem.

In general, the greater the number of transverse
35   filaments used, the better the space charge

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neutralisation of the beam.  On an analysing magnet
with a radius of 40 cm, for example, good space charge
neutralisation can be achieved using around 20
filaments.

5          Fig. 8 shows part of another embodiment in which
the thermionic electron source is arranged inside the
flight tube 2 (or beam vacuum chamber) and at least
partially in the nominal path of the beam.  The
thermionic electron source comprises an array of
10    filaments 5, arranged in a "zig-zag" pattern between
the top and bottom of the flight tube 2 and extending
along the nominal centre line of the beam. The array
thus lies substantially on a curved path along the
beam centre and extends over the full "height" of the
15    beam (the "height" being defined as the extent of the
beam in a direction parallel to the applied field B).

          The filaments are attached to the flight tube 2
by a series of insulators 60.

          In this embodiment the filaments 5 are formed
20    from refractory material and are arranged to be heated
by the beam only.  In other embodiments the filaments
may be heated electrically at least in part, and may
be connected electrically in series or in parallel.
In these other embodiments, appropriate electrical
25    feedthroughs to the filaments are provided.

          In alternative embodiments, the thermionic
electron source may be a grid arranged at least
partially inside the nominal beam envelope.

          Fig. 9 shows a schematic cross section of part of
30    another embodiment, in which the thermionic electron
source comprises a substantially planar array of
filaments 5 arranged across the nominal centre of the
beam envelope 31, the filaments being heated, at least
in part, electrically by a current supplied by means
35    of bus bars 6 at the sides of the beam path.  The

flight tube 2 is earthed, and the array of filaments 5
is negatively biased with respect to the flight tube
to control the energy of electrons injected into the
beam.

5          Electron repellers 51a are arranged above and
below the nominal beam envelope 31 and are each
negatively biased with respect to the filament array
5.  All bias voltages are adjustable.

          Low energy emitted electrons 70 may be confined
10   in the beam by the beam potential well, whereas more
energetic electrons 71 may escape the beam but be
reflected back into it by the repellers 51a.

          It will be apparent from the preceding
description that the present invention is not limited
15   in its application to the neutralisation of beam space
charge in analysing magnets, and may be applied in
other regions of applied magnetic field, which may be
static or varying, for example, in bending or scanning
magnets.

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CLAIMS

1.    Ion beam apparatus comprising:
      an analysing magnet including a flight tube for
5     receiving and conveying through the magnet a beam of
      ions, the magnet being operable to generate a
      substantially uniform magnetic field in the flight
      tube to deflect beam ions according to their
      mass/charge ratio in a dispersion plane perpendicular
10    to the direction of said uniform magnetic field; and
      a thermionic electron source inside the flight
      tube, arranged adjacent and outside a nominal cross
      section of a beam of ions travelling through the
      magnet and extending along a nominal flight path of a
15    beam travelling through the magnet,
      the thermionic electron source being further
      arranged such that the projection of the thermionic
      electron source on the dispersion plane and the
      nominal projection on the dispersion plane of an ion
20    beam travelling through the magnet overlap at a
      plurality of positions along the nominal flight path
      of the beam.

2.    Ion beam apparatus in accordance with claim 1,
25    wherein the thermionic electron source extends along
      the nominal flight path substantially in a plane
      spaced from and parallel to the dispersion plane.

3.    Ion beam apparatus in accordance with claim 1 or
30    claim 2, wherein the thermionic electron source
      comprises an electrically conductive filament arranged
      to emit electrons thermionically and extending along
      the nominal flight path and positioned substantially
      parallel to the nominal centre of a beam of ions
35    travelling through the magnet, the filament having a

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projection on the dispersion plane which for at least
a substantial part of the length of the filament
overlaps the nominal projection on the dispersion
plane of a beam of ions travelling through the magnet.

5

4.    Ion beam apparatus in accordance with claim 3
comprising a plurality of said electrically conductive
filaments arranged such that the projections of said
filaments on the dispersion plane lie substantially
10    parallel to each other and are spaced apart across the
width of the nominal projection of the beam on the
dispersion plane.

5.    Ion beam apparatus in accordance with claim 1 or
15    claim 2 wherein the thermionic electron source
comprises a plurality of electrically conductive
filaments arranged to emit electrons thermionically,
each filament having a projection on the dispersion
plane extending across at least part of the width of
20    the nominal projection on the dispersion plane of a
beam of ions travelling through the magnet, said
filaments being spaced apart from each other along the
nominal flight path.

25    6.    Ion beam apparatus in accordance with claim 5
wherein the projection of each said filament extends
fully across the width of the nominal beam projection.

7.    Ion beam apparatus in accordance with claim 5 or
30    claim 6 wherein each said filament has a substantially
hairpin-like geometry.

8.    Ion beam apparatus in accordance with any one of
claims 3 to 7 wherein said filament or each of said
35    plurality of filaments comprises tungsten.

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9.    Ion beam apparatus in accordance with any one of claims 3 to 7 wherein said filament or each of said plurality of filaments comprises carbon.

10.   Ion beam apparatus in accordance with any preceding claim further comprising at least one heat shield arranged between the thermionic electron source and the inside of the flight tube.

11.   Ion beam apparatus comprising:
      an analysing magnet including a flight tube for receiving and conveying through the magnet a beam of ions, the magnet being operable to generate a substantially uniform magnetic field in the flight tube to deflect beam ions according to their mass/charge ratio in a dispersion plane perpendicular to the direction of said uniform magnetic field; and
      a thermionic electron source inside the flight tube, extending along the nominal flight path of said beam and being arranged inside the nominal envelope of said beam.

12.   Ion beam apparatus in accordance with claim 11, wherein said thermionic electron source comprises an array of filaments, said array extending along the nominal centre of said beam.

13.   Ion beam apparatus in accordance with claim 12, wherein said array extends at least partially across the nominal height of said beam in the direction of said uniform magnetic field.

14.   Ion beam apparatus in accordance with claim 13, wherein said array lies substantially on a curved surface, said curved surface having the same

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projection on the dispersion plane as the nominal beam
centre line.

15.   Ion beam apparatus in accordance with claim 12,
wherein said array is substantially planar and
parallel to the dispersion plane.

16.   Ion beam apparatus in accordance with any one of
claims 12, 13 and 15 wherein said array extends at
least partially across the nominal width of said beam
in a direction parallel to the dispersion plane.

17.   Ion beam apparatus in accordance with any one of
claims 12 to 16, wherein said filaments are
electrically conductive.

18.   Ion beam apparatus in accordance with claim 17,
wherein said filaments comprise carbon

19.   Ion beam apparatus in accordance with any one of
claims 12 to 18, wherein said filaments comprise
refractory material.

20.   Ion beam apparatus in accordance with any one of
claims 11 to 19, further comprising a selection slit
arranged to admit only a selected portion of ions
conveyed through said magnet to the remainder of said
apparatus, said thermionic electron source being
arranged such that no part of the source inside the
nominal beam envelope is in direct line of sight with
said selection slit.

21.   Ion beam apparatus comprising:
      a magnet arranged to generate a magnetic field in
a flight tube to deflect a beam of ions travelling

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through said flight tube; and
    a thermionic electron source inside said flight
tube, extending along the nominal flight path of said
beam and arranged to emit electrons thermionically
5    into said beam.


22.   Ion beam apparatus in accordance with claim 21,
wherein said thermionic electron source is arranged
adjacent and outside the nominal envelope of said beam
10    in said flight tube and is further arranged to be
linked to said beam at a plurality of position along
said nominal flight path by magnetic flux generated by
the magnet.


15    23.   Ion beam apparatus in accordance with claim 21,
wherein at least part of said thermionic electron
source is arranged inside the nominal envelope of said
beam.


20    24.   Ion beam apparatus in accordance with any one of
claims 21 to 23, wherein said thermionic electron
source comprises an array of filaments.


25.   Ion beam apparatus in accordance with claim 24,
25    herein said array is substantially planar and
perpendicular to said magnetic field.


26.   Ion beam apparatus in accordance with any
preceding claim, further comprising a supply of
30    charge-neutral atoms or molecules arranged to
introduce said atoms or molecules into the flight tube
for ionisation by thermionically emitted electrons.


27.   Ion beam apparatus in accordance with any
35    preceding claim wherein said thermionic electron

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source is arranged to have a negative bias voltage
with respect to the flight tube.

28.    Ion beam apparatus in accordance with claim 27
5      wherein the negative bias voltage of said thermionic
electron source is adjustable.

29.    Ion beam apparatus in accordance with any
preceding claim, further including an electron
10     repeller arranged inside the flight tube, outside the
nominal beam envelope, and between the thermionic
electron source and a wall of the flight tube, the
electron repeller being substantially planar and
extending along the nominal flight path of the beam,
15     the projection of the electron repeller onto a plane
perpendicular to the direction of said magnetic field
at least partially overlapping the nominal projection
of said beam onto said plane, the electron repeller
being further arranged to have a negative bias voltage
20     with respect to the thermionic electron source.

30.    Ion beam apparatus in accordance with claim 29,
wherein the negative bias voltage of the electron
repeller is adjustable.
25
31.    Ion beam apparatus in accordance with claim 29 or
claim 30, wherein the electron repeller comprises a
sheet of graphite.

30     32.    Ion beam apparatus in accordance with any one of
claims 29 to 31, wherein the electron repeller is also
a heat shield.

33.    Ion beam apparatus in accordance with any one of
35     claims 29 to 32, further comprising a second said

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electron repeller, the electron repeller and second
electron repeller being arranged on opposite sides of
the beam.

5       34.   A method of neutralising space charge in a beam
        of ions travelling in a flight tube through a magnet,
        the method comprising the steps of:
             providing a source of thermionic electrons inside
        the flight tube, adjacent and outside the nominal
10      cross section of the beam and extending along the
        nominal flight path of the beam;
             arranging the thermionic electron source to be
        linked to the beam at a plurality of positions along
        the nominal flight path by magnetic flux generated by
15      the magnet; and
             emitting electrons thermionically from the
        thermionic electron source.

        35.   A method in accordance with claim 12 further
20      comprising the step of arranging the thermionic
        electron source to be linked to the beam at a
        plurality of positions across the width of the beam by
        magnetic flux generated by the magnet.

25      36.   A method of neutralising space charge in a beam
        of ions travelling in a flight tube through a magnet,
        the method comprising the steps of:
             providing a source of thermionic electrons inside
        the beam, said source extending along the beam; and
30      emitting electrons thermionically from said source.

        37.   A method in accordance with any one of claims 34
        to 36, further comprising the steps of:
             negatively biasing the thermionic electron source
35      with respect to the flight tube; and

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adjusting the negative bias of the thermionic
electron source to control the energy of the emitted
electrons.

5       38.  A method in accordance with any one of claims 34
to 37, further comprising the step of reflecting
electrons escaping the beam back towards the beam
using at least one negatively biased electron
repeller.

10

39.  A method in accordance with any one of claims 34
to 38, further comprising the steps of introducing
charge-neutral atoms or molecules into the flight tube
and ionising said atoms or molecules with said
15      thermionically emitted electrons.

40.  Ion beam apparatus substantially as hereinbefore
described with reference to the accompanying drawings.

20      41.  A method of neutralising space charge
substantially as hereinbefore described with reference
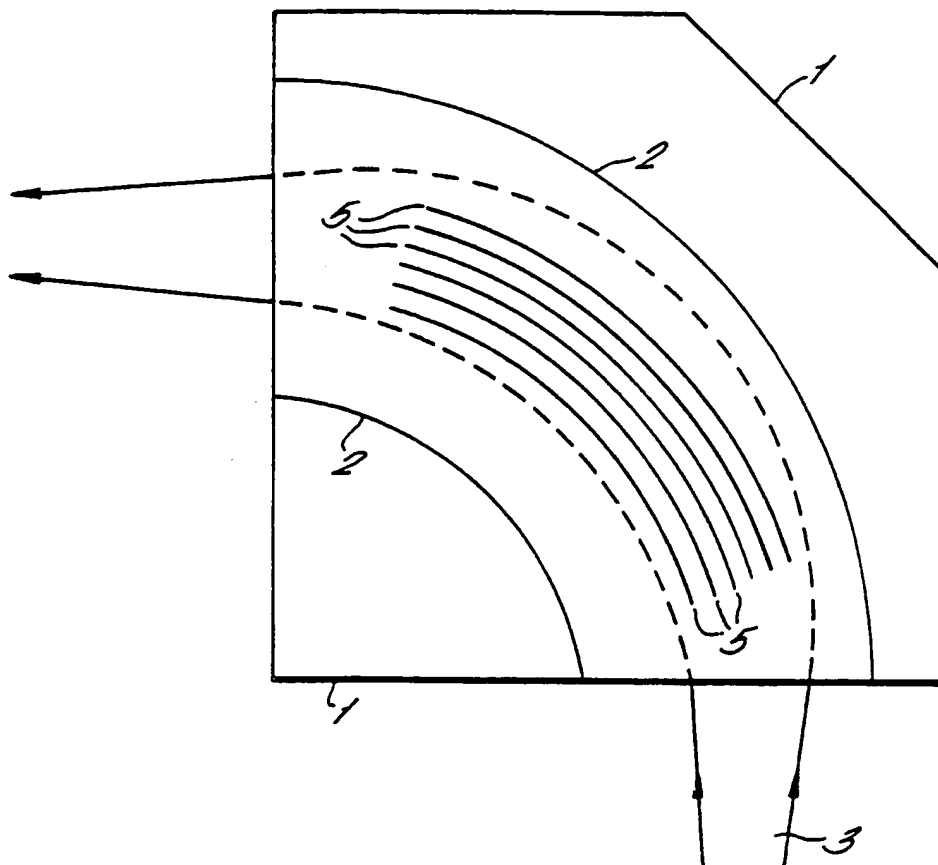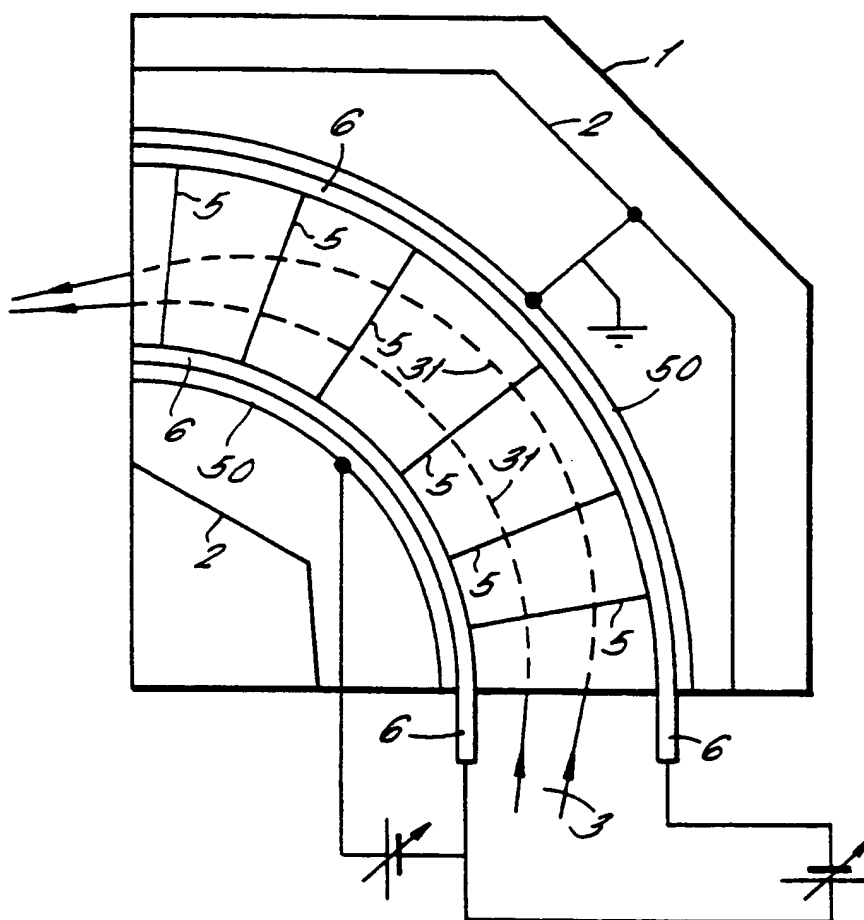to the accompanying drawings.

FIG. 1.

FIG. 2.

*FIG. 3.*

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FIG. 4.

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FIG.5.

FIG. 6.



FIG. 7.
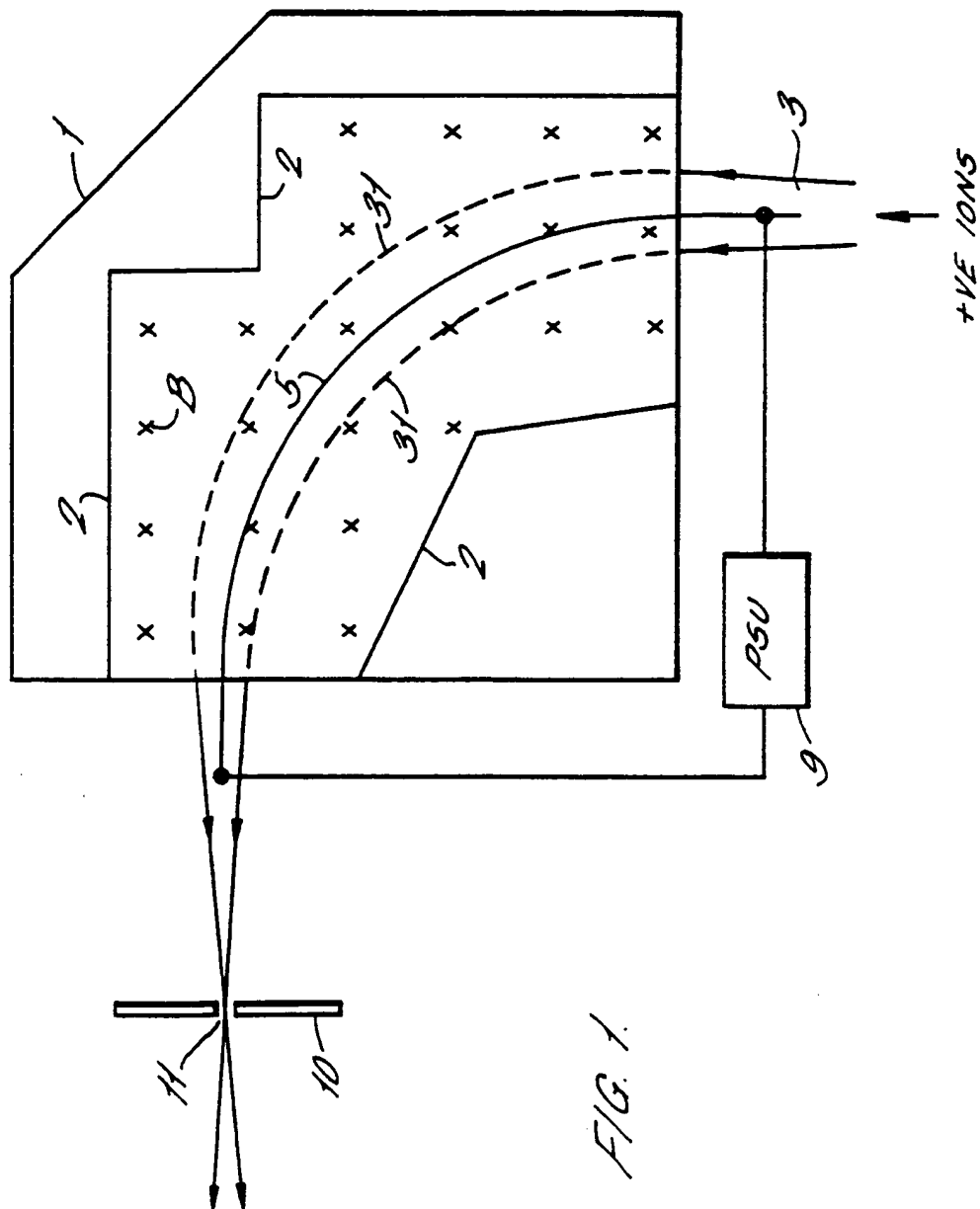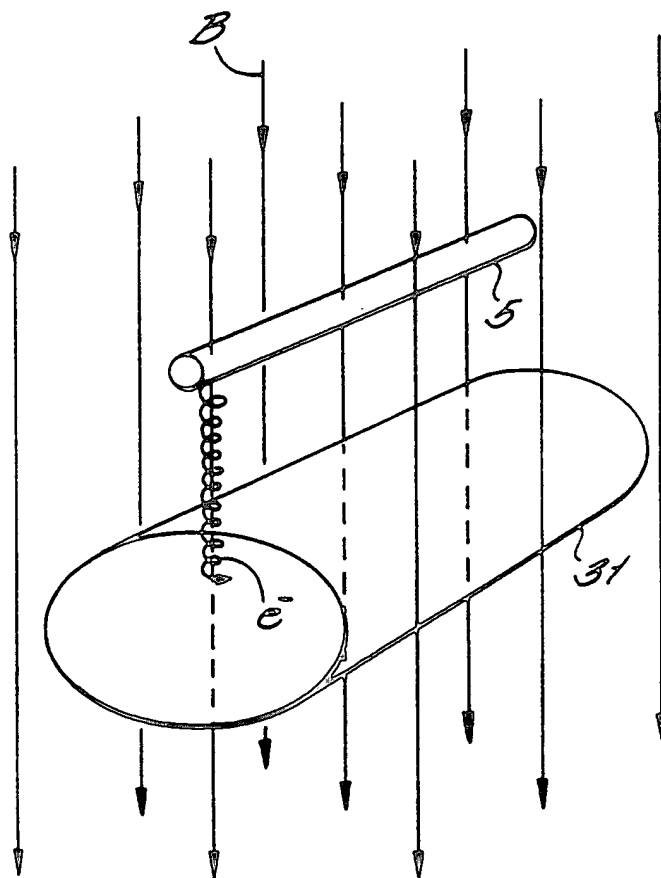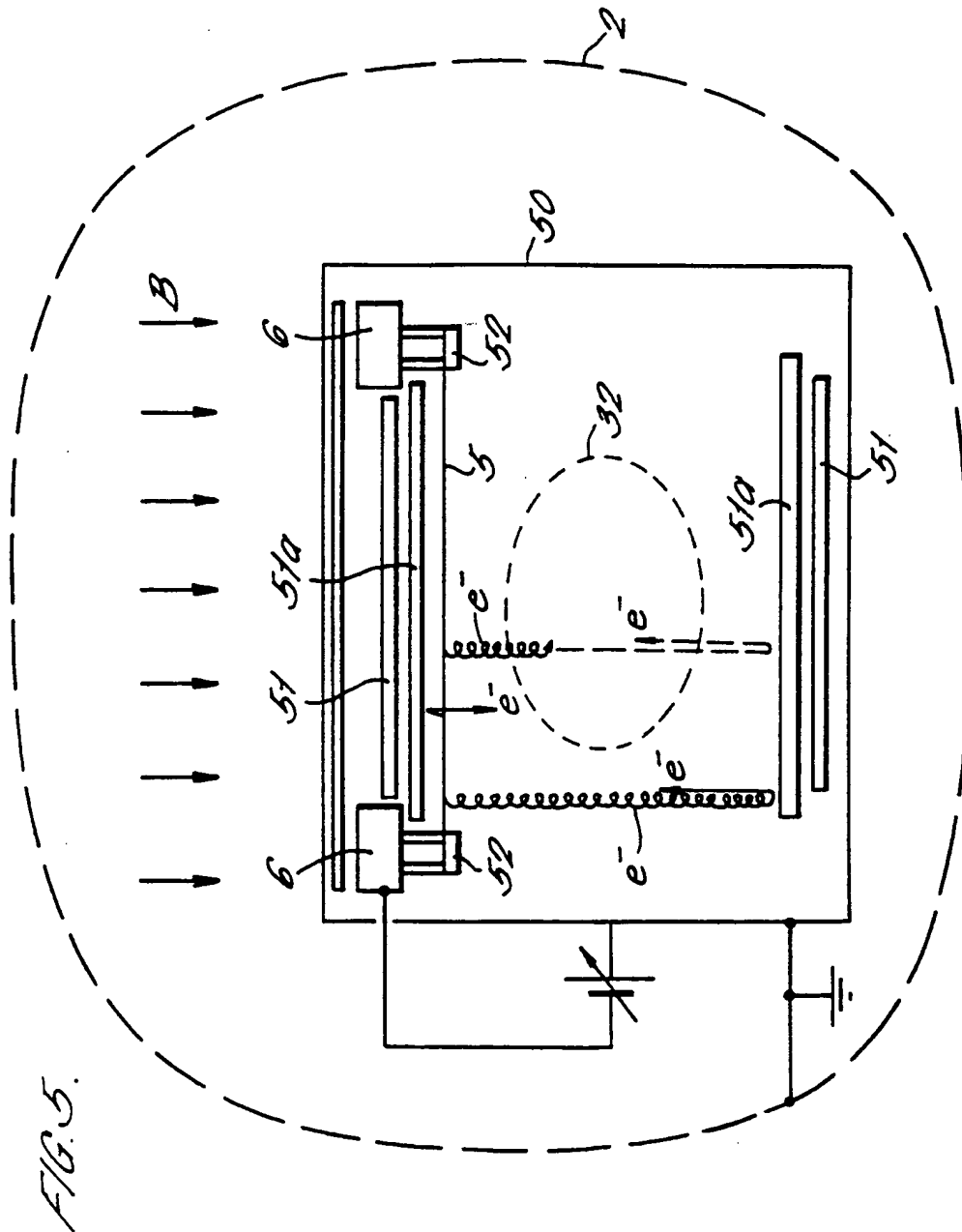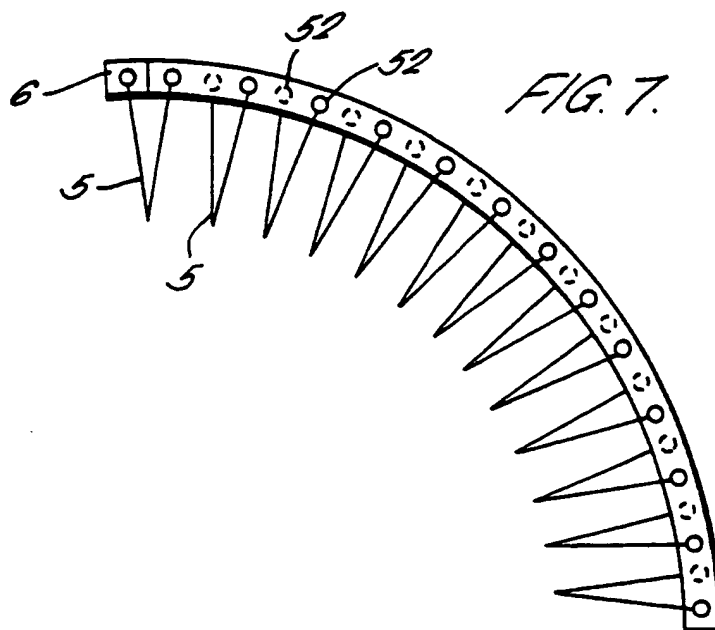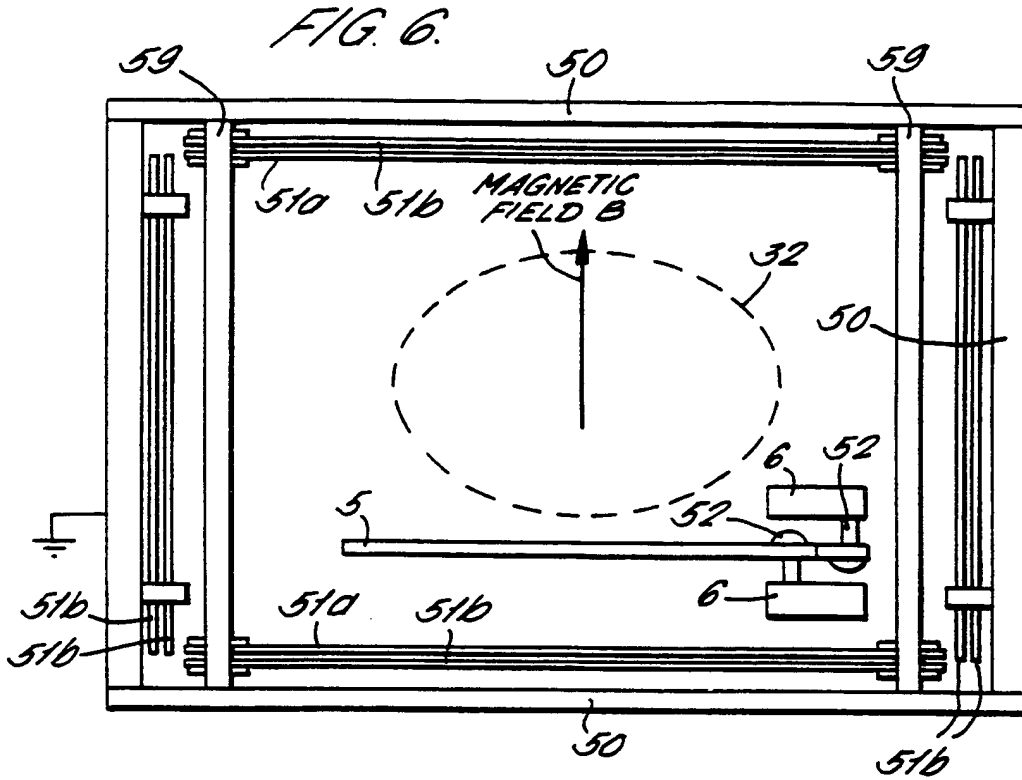
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FIG. 8.
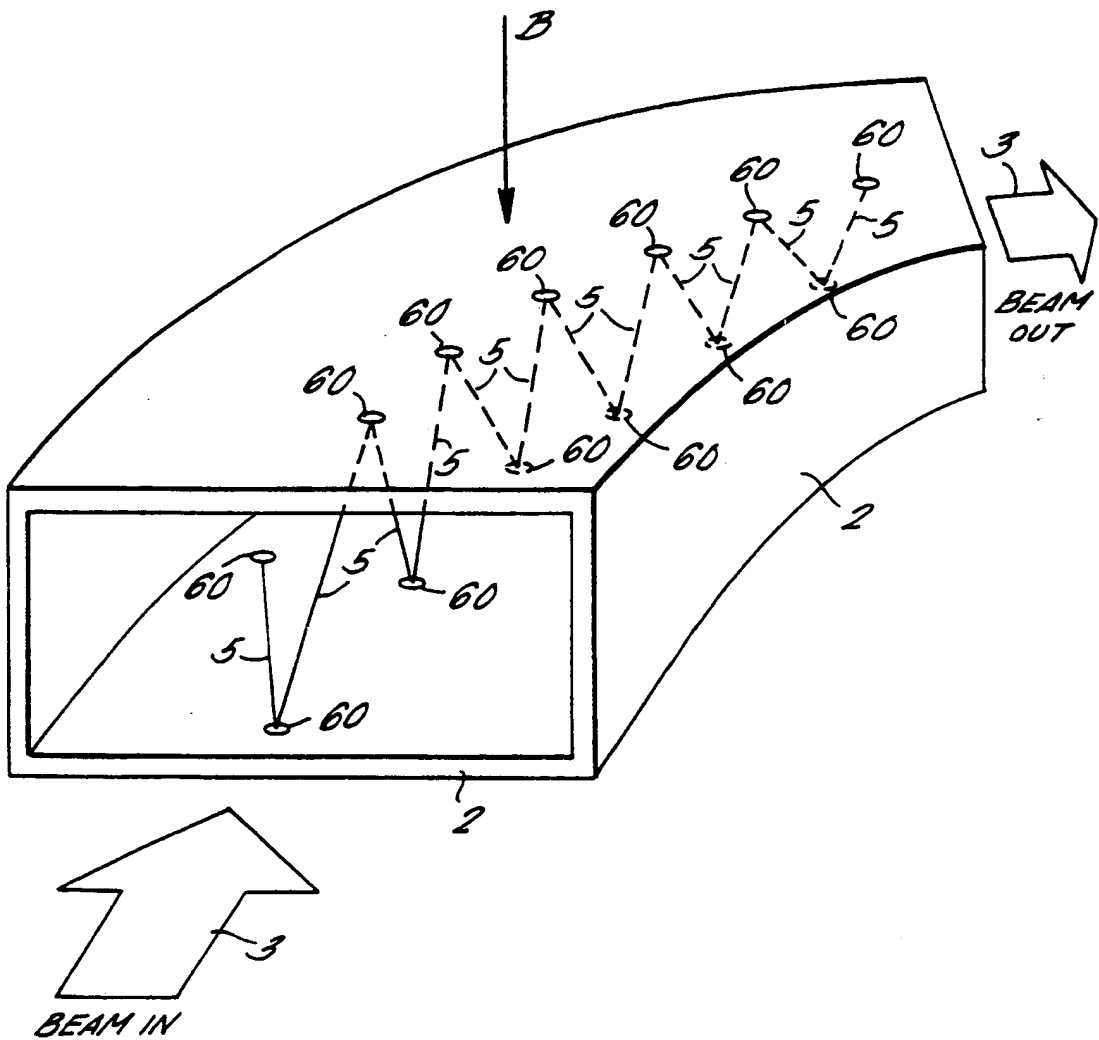
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FIG. 9.
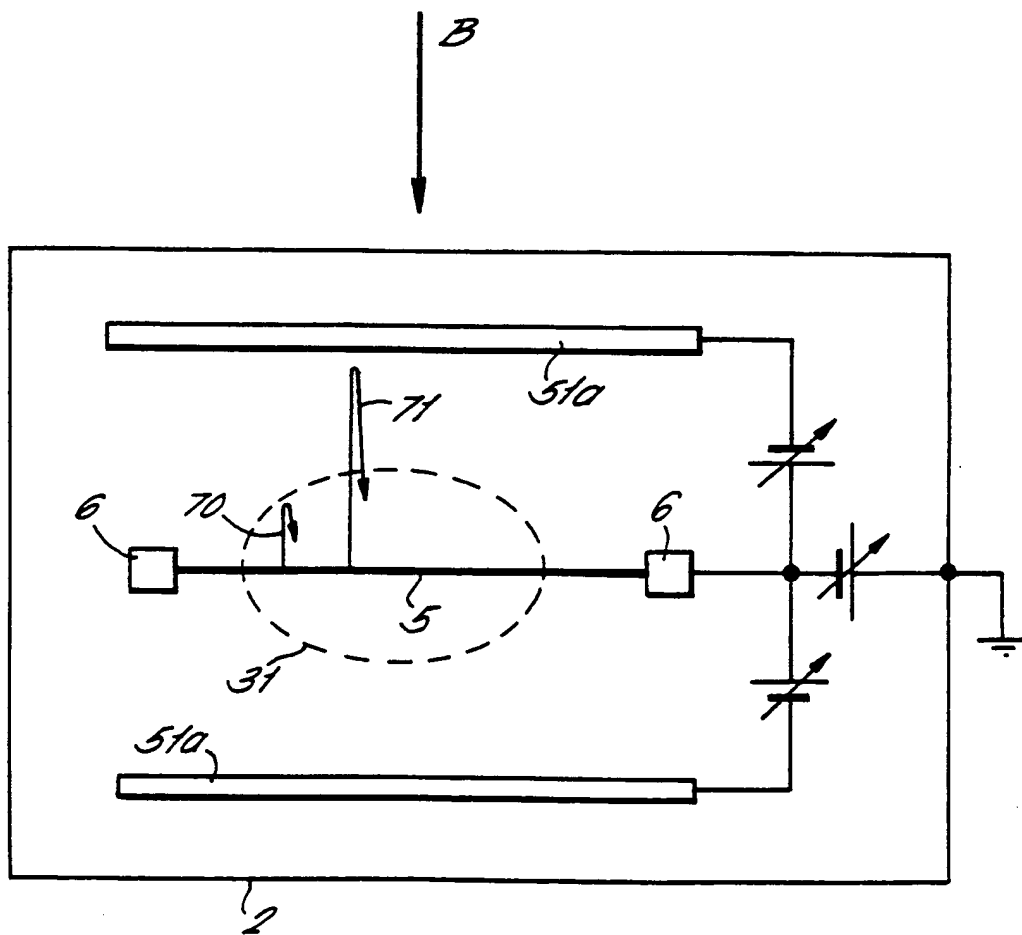
# INTERNATIONAL SEARCH REPORT

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC 6   H01J37/02     H01J37/317    H01J49/02

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 6   H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | PATENT ABSTRACTS OF JAPAN<br>vol. 199, no. 711,<br>28 November 1997 (1997-11-28)<br>& JP 09 180662 A (HITACHI LTD),<br>11 July 1997 (1997-07-11)<br>abstract | 1,11,21,<br>34 |
| A | LEUNG K N ET AL: "AN ELECTRON-BEAM CHARGE NEUTRALIZATION SYSTEM FOR ION IMPLANTERS" NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH, SECTION - B: BEAM INTERACTIONS WITH MATERIALS AND ATOMS,<br>vol. B55, no. 1 / 04,<br>2 April 1991 (1991-04-02), pages 94-96,<br>XP000230669<br>ISSN: 0168-583X<br>page 94 -page 95; figure 1 | 1,11,21,<br>34 |

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| [X] Further documents are listed in the continuation of box C. | [X] Patent family members are listed in annex. |
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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 30 September 1999 | 06/10/1999 |

| Name and mailing address of the ISA<br>European Patent Office, P.B. 5818 Patentlaan 2<br>NL – 2280 HV Rijswijk<br>Tel. (+31–70) 340–2040, Tx. 31 651 epo nl,<br>Fax: (+31–70) 340–3016 | Authorized officer<br><br>Schaub, G |
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Int' ational Application No

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category ³ | Citation of document, with indication,where appropriate, of the relevant passages | Relevant to claim No. |
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| A | US 4 886 971 A (MATSUMURA YASUSHI ET AL) 12 December 1989 (1989-12-12) abstract; figures | 1,11,21, 34 |
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